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COSMIC RAY EFFECTS IN VERY LARGE SCALE INTEGRATION

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Abstract

The reduced size and operational energy associated with microelectronic circuitry has created a situation wherein a cosmic ray, in a single pass, can generate a false signal or otherwise damage a circuit element. In this work an analytic expression for the event rate of false signals (a.k.a. soft errors) is derived, based upon the geometric probability of a cosmic-ray track occurring in the sensitive volume of a microcircuit device. The analyses show that substantial reduction in the soft error rates from heavy cosmic rays can be achieved by device designs which incorporate large operational energies and small depletion collection volumes. The permanent damage to oxide layers in metal-oxide-semiconductor (MOS) devices is estimated. The special role of protons as initiators of soft errors and permanent damage is explored. These processes are then described in the context of very large scale integration (VLSI) electronics in Earth satellite environment. Proton non-elastic scatter events which produce energetic recoiling Silicon nuclei are identified as the chief cause of proton initiated soft errors.

Introduction

Microelectronic circuits (VLSI) subjected to cosmic-ray or other heavy ion bombardment undergo false switching-error writing response. The requirement of the circuit to produce such a response is the deposition of a threshold amount of energy in the form of ionizing reactions in a small fairly well-defined volume of the circuit. The requirements for the ion or cosmic ray are that the energy be sufficient to penetrate any shielding, with kinetic energy in excess of the circuit threshold, ΔE , and linear energy transfer great enough to deposit ΔE in a track whose length is only several microns.

This work describes the dose distribution surrounding a cosmic-ray track and the impact of that energy deposition in

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the form of hole-electron pairs in VLSI circuitry, specifically as it applies to dynamic Random Access Memories. An event rate for errors in satellite borne electronics exposed to the cosmic flux is derived. The possibilities of permanent damage to the oxide layers in MOS devices are described, and finally the role of protons in these interactions is developed.

Size and Dose Distributions near Heavy Ion Tracks

When a fast heavy ion penetrates condensed matter, some of the orbital electrons are stripped from the ion, and a beam of such ions then has a mean ionic charge, $z < Z$; z has been measured widely as a function of energy and velocity of the ion and is given by Barkas¹

$$z = Z(1 - e^{-15\beta Z^{-2/3}}) \quad (1)$$

The ion loses energy through electron collisions and generates electron flux at a rate given by Mott²

$$\frac{dn}{d\omega} = \frac{2\pi N z^2 e^4}{m v^2} \cdot \frac{1}{\omega^2} \left[1 - \beta^2 \frac{\omega}{\omega_m} + \frac{\pi \beta z}{137} \left(\frac{\omega}{\omega_m} \right)^{1/2} \left(1 - \frac{\omega}{\omega_m} \right) \right] \quad (2)$$

where $dn/d\omega$ = the number of electrons between energy ω , $\omega + d\omega$ generated per cm of ion track in matter containing N electrons/cm³ and $\omega_m = 2mc^2\beta^2\gamma^2$; e , m are the electron charge and mass and $\beta = v/c$.

The above electron generation mechanisms can be coupled with electron transport models to produce a relatively detailed picture of the dose and electron flux near a heavy ion track. Kobetich and Katz³ and Hamm⁴ have made extensive calculations of the energy deposited near an ion track with the following result:

$$D = kz^2/r^2 \quad (3)$$

That is, the energy deposition, D , in ergs/g at radius r from a cylindrical track falls off as $1/r^2$ and is proportional to z^2 , where, from Eq. 1 above, z is the mean ionic charge of the ion or cosmic ray. Both z and k are functions of β . Recent measurements at Brookhaven⁵ have verified the $1/r^2$ dependence over a range of 1 to 300 nm (10 Å), as shown in Fig. 1.

The column of ionization which a fast heavy ion leaves in its wake contains central core energy densities of 8×10^{20} eV/cm³ for protons to 10^3 times greater for heavy cosmic rays

(e.g., Fe^{56}). The track can be viewed as a cylinder whose radius is approximately 1μ and within which the dose falls off from the center as r^{-2} . For this work it is the size of the cylinder in relation to the size of electronic devices, as shown in Fig. 2, and the energy deposited therein that is of interest.

Track Length Distribution in 3-Dimensions

Recent increases in the density of planar technology electronic microcircuits have led to devices which are capable of interruption by the passage of a single cosmic ray or other highly ionizing particle. One of the more prominent of these is the dynamic random access memory cell of the MOS type. The interaction of fast heavy ions with MOS memory cells can create writing errors. Two sources have been identified: 1) cosmic rays⁶⁻⁸ and 2) uranium and/or thorium α decay⁹ from ceramic packaging materials adjacent to the memory cell. The underlying requirement for memory cell upset is the deposition of an amount of energy, greater than some threshold energy, which

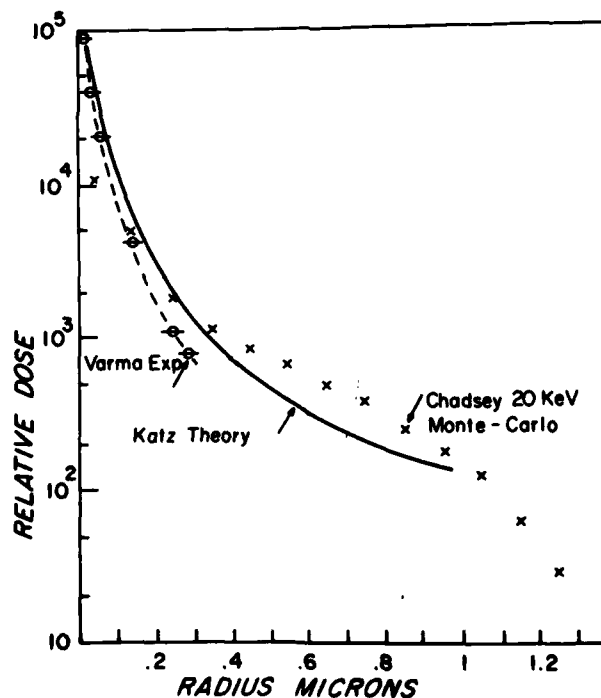


Fig. 1 Comparison of radial distributions for heavy ions, SEM electron beams, theory, and experiment.

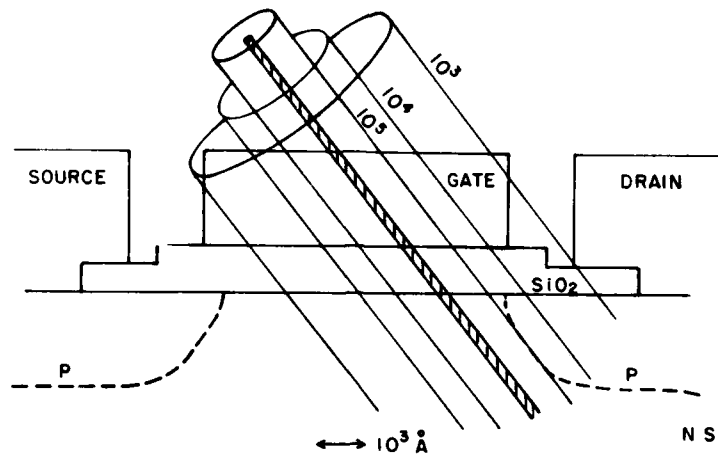


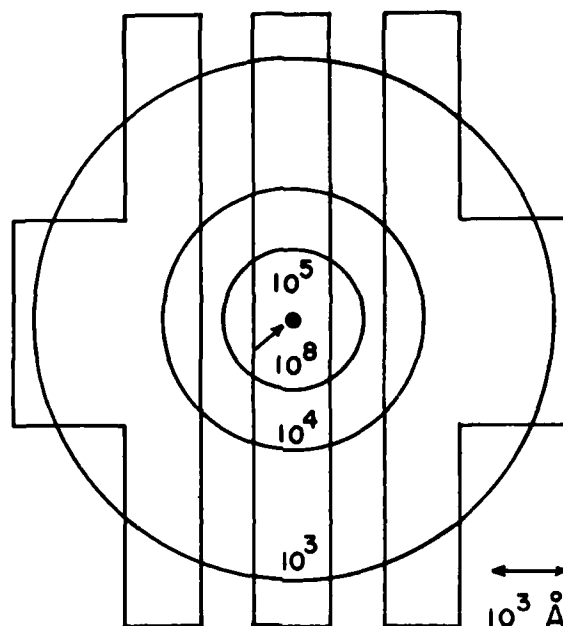
Fig. 2 Heavy ion track in perspective of an MOS device of VLSI size. Concentric circles are dose in rads in silicon.

generates an electron-hole pair flux. The subsequent collection of the charges causes a writing error. The energy must be deposited in the sensitive region of the device, i.e., where the charges are collectable. In general that region is near the gate and source of the MOS device. The possibility of large diffusion lengths enlarges that region. The dose surrounding a cosmic-ray track as it impinges normally on an MOS structure is shown in Fig. 3.

Analysis

The approach to the problem taken here is to treat the collection volume (sensitive volume) of the electronic device as a right rectangular volume. The cosmic rays traverse this volume without deflection, and the tracks are thus straight lines. This permits a solution based on the geometric probability of the chord lengths generated when a convex volume (surface everywhere characterized by a positive radius of curvature) is immersed in a uniform isotropic flux.

An ion moving through matter loses energy at a rate called its LET (linear energy transfer). For small distances this loss rate is a constant. The total energy lost by the ion is the LET \times ℓ , where ℓ is the track length in the region of interest. The assumptions of this work are that the heavy ion tracks in question are straight lines and that the volume of interest is a rectangular parallelepiped, $h \times a \times b$, $h < a$



SOURCE GATE DRAIN

Fig. 3 Dose distribution surrounding a heavy ion track normal to VLSI device.

< b. Actual typical dimensions are $h \sim 2\mu$; $a, b \sim 20\mu$ in large scale integration (LSI) and $h, a, b < 1\mu$ in VLSI.

What is required is the probability that a cosmic-ray track length, within the collection volume, is greater than or equal to the minimum length needed for the electronic response to occur. The probability distribution which answers that requirement is called the sum distribution. The sum distribution for chord lengths in a rectangular volume, $C(\ell)$, was determined exactly from the work of Coleman¹⁰ who solved the problem for the 2-dimensional rectangle and unit cube, of Kellerer¹¹ who developed the formalism which leads to the 3-dimensional sum distribution for right cylinders of arbitrary cross section, and of Bradford¹² who applied the formalism to a rectangular parallelepiped.

The resulting analytic functions $C(\ell)$ are plotted in Figs. 4 and 5 for several cases. The symmetry of the infinite plane slab and the sphere permits easier evaluation of the

integrals, and they are shown for references. The distribution for the unit cube is shown, as is the distribution for a volume $h \times 4h \times 6h$. The latter curve is pertinent to the attempts of Pickel and Blandford⁸ to predict an event rate for cosmic-ray interruption of satellite borne electronics. The volume in question is the sensitive volume of each of 24 4K RAM memory cells, generally that volume defined by the source-to-drain area and depletion depth.

We can compute an event rate for electronic interrupt using $C(l)$ by noting that any convex body immersed in a uniform, isotropic flux, ϕ particles/cm²/sec, will experience $(\phi S/4)$ transits/s, where S is the total surface area.

$\phi(x)$, the LET spectrum, specifies the particle flux for each value of LET. A minimum track length along which sufficient energy is deposited to cause the electronic response to occur is determined by each LET value. The relationship which leads to that minimum track length is

$$l = \frac{\Delta E_{\text{threshold}}}{\text{LET} \cdot \rho}$$

where ρ is the density and the ΔE threshold is the minimum energy deposition required for electronic response. $C(l)$ then gives the fraction of track lengths generated by the

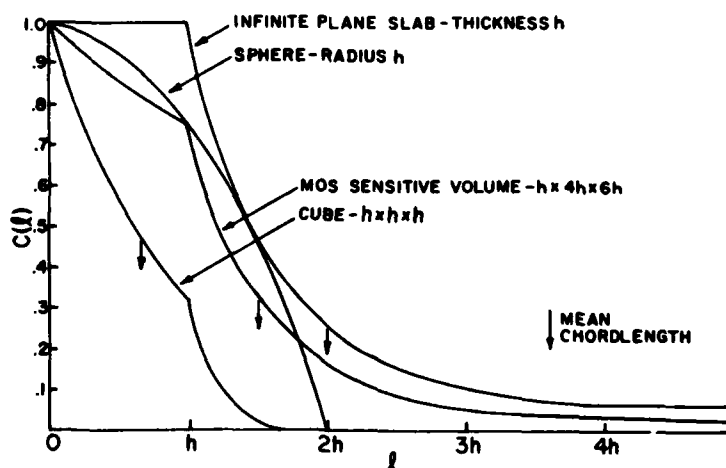


Fig. 4 Sum distribution functions for chord lengths in various geometries.

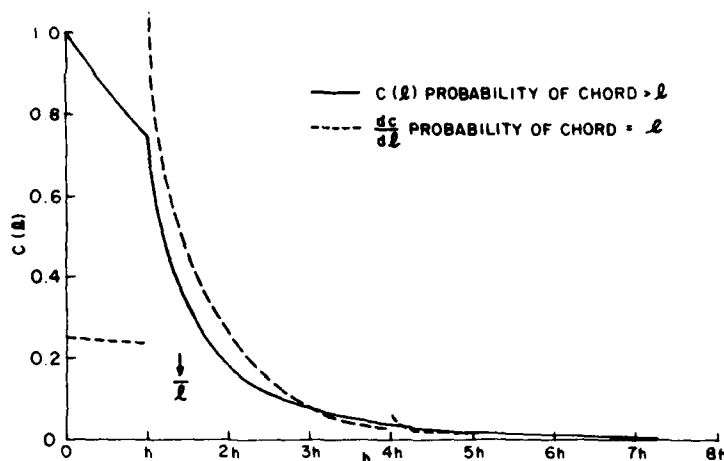


Fig. 5 Differential and sum distributions for track lengths in VLSI device. Volume is of rectangular shape, $h \times 4h \times 6h$.

particle flux with that LET value which can cause the electronic response. Integration over the LET spectrum then yields the total event producing combinations of LET and sufficient track length. The event rate thus is given by

$$n = S/4 \int_{x_0}^{x_1} \phi(x) C(\Delta E/\rho x) dx \text{ events per sec per device} \quad (4)$$

assuming 100% efficiency for the process (e.g., charge collection), $\phi(x)$ is the LET flux in particles/[$\text{cm}^2 \cdot \text{s} \cdot (\text{MeV cm}^2/\text{g})$], x is LET in $\text{MeV cm}^2/\text{g}$ and $\psi = \int \phi(x) dx$

Since $C(l)$ is a reasonably complicated function, the event rate integral usually requires machine solution. An approximation can be obtained by noting that the dominant terms in $C(l)$ fall off like $1/l^r$, $r > 2$ and that $\phi(x) \sim \phi_0 (x_0/x)^P$, $P = 3.8$.¹³ Equation (4) is thus reducible to simple form by taking the following definitions for the integrand:

$$\begin{aligned} \phi(x) &= (x_0)(x_0/x)^P = 16 \times 10^{13} (10^3/x)^{3.8} \\ &\text{particles}/[\text{m}^2 \cdot \text{s} \cdot (\text{MeV cm}^2/\text{g})] \end{aligned} \quad (5a)$$

with the values for x_0 , $\phi(x_0)$, P taken from Ref. 13. For $C(l)$ take

$$C(l) = C(h)(h/l)^{2.2} = 0.75 (h\rho x/\Delta E)^{2.2} \quad (5b)$$

as a reasonable approximation for chord lengths greater than h in rectangular volumes.¹²

$$x_0 = \Delta E / \rho \ell_{\max} = 10^3 \text{ MeV cm}^2/\text{g} \quad (6a)$$

$$x_1 = \Delta E / \rho \ell_{\min} = 7 \times 10^3 \text{ MeV cm}^2/\text{g} \quad (6b)$$

are the limits in the integral of Eq. (4), where the numbers are for the 4K RAM of Ref. 8. The effect of these limits in determining the portion of two species C and Fe of the cosmic spectrum, which can participate in that case, is shown in Figs. 6 and 7.

The general solution is obtained by retaining the definitions of the limits following integration of Eq. 4 and the event rate, n , is given by

$$\begin{aligned} n &= 7.5 \times 10^{-7} NS(h\rho/\Delta E)^{2.2} [(x_0)^{-0.6} - (x_1)^{-0.6}] \\ &= 7.5 \times 10^{-7} NS(h\rho/\Delta E)^{2.2} [(\rho \ell_{\max}/\Delta E)^{0.6} - (\rho \ell_{\min}/\Delta E)^{0.6}] \\ &= 7.5 \times 10^{-7} NS(h\rho/\Delta E)^{2.8} [(\ell_{\max}/h)^{0.6} - 1] \\ &= 7.5 \times 10^{-7} NS(h\rho/\Delta E)^{2.8} [(10\Delta E/h\rho)^{0.6} - 1] \text{ events/} \end{aligned}$$

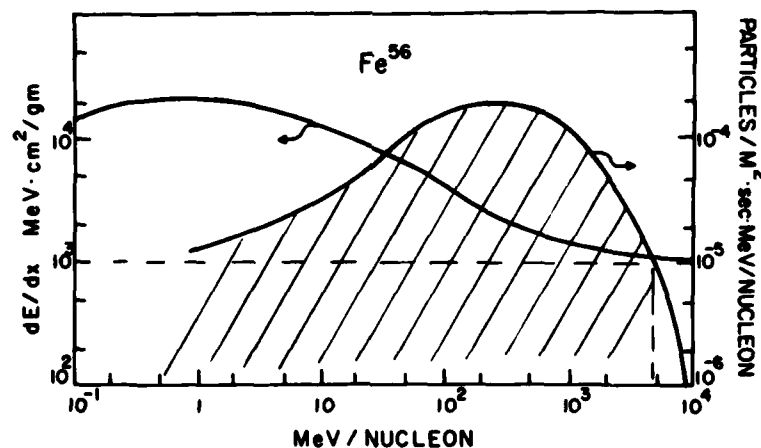


Fig. 6 Cosmic flux for Fe^{56} with LET values for the same energy range. Shaded area shows population which can cause electronic interrupt of Ref. 8.

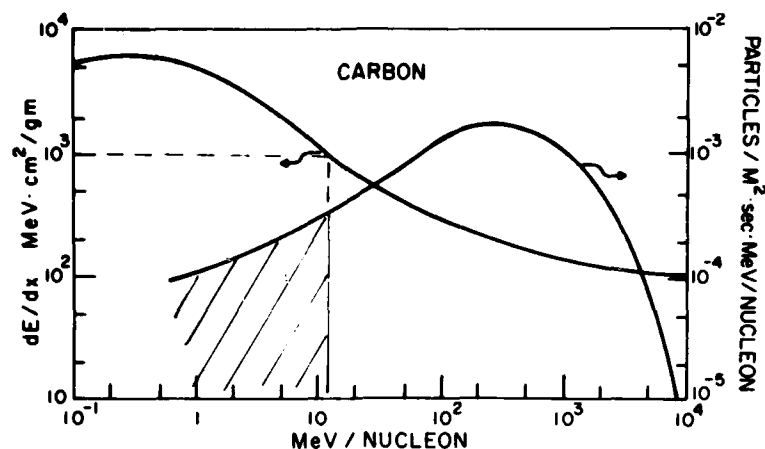


Fig. 7 Cosmic flux for C12 with LET values for the same energy range. Shaded area shows population which can cause electronic interrupt of Ref. 8.

Since $\ell_{\min} = h$ in this approximation, ℓ_{\max} is the major diagonal of the volume. This result is valid for cosmic ray flux with $\text{LET} > 10^3 \text{ MeV cm}^2/\text{g}$, where

S = surface area of device sensitive volume in μ^2
 h = device sensitive volume minimum dimension (presumably depletion depth) in μ

ΔE = switching energy in MeV

N = number of devices

ρ = density in g/cm^3

This result is based on the unshielded LET spectrum of Heinrich¹³ for $6 < z < 26$. To take shielding into account one need only multiply these results by an attenuation factor from Heinrich's paper, $-e^{-3.91(t/50)}$, where t is shield thickness in g/cm^2 . This factor applies only to the total LET spectrum $> 10^3$, not to any individual species.

The event rate, Eq. (7), can be used by electronics designers or system analysts to anticipate soft error rates in satellite-borne electronics devices. The basic requirement for such utilization is to identify those memory cells or switches which can be characterized as having a rectangular collection volume and within which a threshold energy deposition, ΔE , can be specified. By way of example, when the numbers from the Pickel and Blandford⁸ analysis of the 4K RAMs in satellites are used in Eq. (11), one gets 203 events/year for the 98,309 cells involved. This compares reasonably well with the rate calculated in Ref. 8.

Equation (7) has further merit in that it demonstrates the event rate sensitivity to physical parameters. Clearly emphasized is the necessity to scale the minimum dimension, h (depletion depth), faster than the threshold energy, ΔE , as one designs the higher density VLSI technology. Failure to utilize an analysis which includes the track length distribution can be seen in Ref. 8 where the mean chord length is used instead of the full distribution. This leads to the erroneous conclusion in that paper that the minimum LET rate which can produce the electronic error is $4.6 \times 10^3 \text{ MeV cm}^2/\text{g}$, whereas, in fact, it is $9.6 \times 10^2 \text{ MeV cm}^2/\text{g}$. Finally, as is intuitively clear, the longer track lengths can come only from ions with larger angles of incidence to one of the planes of the device. This response to angle of incidence, which agrees with the behavior of $C(\lambda)$, has been measured experimentally.^{14,15} Thus, establishing a threshold energy for the device error sets a limit on the angle of incidence for each LET value.

Permanent Damage (Oxide)

Permanent damage in the oxides of MOS devices occurs when charges are trapped in the oxide. That charge presence causes a shift in the threshold voltage and, with sufficient shift, a disabling of the device. Normally, this effect is of concern to nuclear survivability and is caused by the γ and x-ray fluxes of that environment. Nonetheless, a cosmic ray in a single pass can create enough charge pairs, which are subsequently trapped, to cause threshold shifts. In VLSI the voltage shifts required to disable the device are smaller, and hence one can anticipate that a permanent damage rate will ensue.

Equation (7) can be used to some value in this case. ΔE is set as the energy required to achieve some average dose in the oxide; then

$$\Delta E(\text{MeV}) = 1.6 \times 10^8 D(\text{rads}) V(\text{cm}^3) \quad (8)$$

If the area is shrunk to VLSI dimension with $V = 0.1 \times 1 \times 10^{-12} \text{ cm}^3$, for 10^4 rads or greater, $\Delta E = 0.16 \text{ MeV}$ and $n = 1$ events/year/ 10^5 devices; for 10^3 rads or greater, $\Delta E = .016 \text{ MeV}$, but $E/\lambda_{\text{min}} = 606 \text{ MeV cm}^2/\text{g}$, which violates the validity criterion ($\text{LET} \geq 10^3$) for Eq. (7). Therefore, one must resort to the formal solution of Eq. (4) over the entire LET range for evaluation. Many times as many ions qualify as a result of this lower LET requirement.

One should keep in mind that, because of the dramatic nonuniformity of the dose distribution in the track, even

though the average dose is greater than 10^3 rads, significant regions of the oxide have received $> 10^5$ rads. The response of devices to such nonuniform irradiation is not well established.

Expected Contributions to LSI/VLSI Soft Error Due to Solar and Cosmic Protons

The interaction of heavy ions with microelectronics devices was examined in the preceding section. The nature of the interaction is such as to produce error signals or switching, and the chief means of avoiding those errors seems to be 1) one very small dimension associated with the sensitive volume of the device, 2) large ΔE for writing or switching, and 3) redundant programming or circuits. In all the foregoing analyses the mode of energy deposition is the LET due to ionizing collisions. The foregoing analyses also recognize a minimum in the LET rate necessary to produce the undesirable effects. That minimum is currently about 10^3 MeV cm^2/g , and the cosmic flux greater than that value has been characterized¹³ by a simple exponential [e.g., $\phi(\text{LET}) = \phi_0(x_0/x)^P \cdot \phi_0 = 4 \times 10^{-3} \text{ m}^{-2} \text{ s}^{-1} \text{ MeV}^{-1} \text{ cm}^{-2} \text{ g}$].

The vast majority of the cosmic-ray population has LET rates less than 10^{-3} MeV cm^2/g , however. Protons, for example, have maximum rates of only $\sim 10^2$ MeV cm^2/g at energies of a few MeV. Since the preponderant portion of the proton cosmic flux has LET rates of 2 MeV cm^2/g (480 eV/ μ in Si) for a 1μ size device, the threshold energy, (ΔE_{th}), would need to be as small as 500 eV for protons to qualify for error production via ionization loss. Protons can participate even when ΔE_{th} is large, however, via nuclear reactions and by elastic scattering.

Thus, the role protons play must be examined in two views: 1) in trapped belt or solar flare exposures, in spite of the small LET rates, the flux can be large enough to cause permanent oxide damage through accumulated total dose; 2) cosmic and/or trapped belt plus solar flare exposure with protons acting singly to produce soft errors. The permanent oxide damage is not different from that encountered in x-ray fluxes from nuclear weapons and, since studies of that effect are plentiful in literature, it will not be dealt with here.

Nuclear Interactions

The proton-induced nuclear reactions of interest are p, n; p, 2n; p, pn; p, α ; and p, spall. The mechanism by which these reactions can trigger soft errors is the ionization

energy loss of the recoil residual nucleus and, in the case of the p, α , and p, spall reactions, through the ionization losses of the reaction products. The total proton inelastic scatter cross section rises from a few hundred millibarns at 4 MeV to 1200 mb at 30 MeV and then declines to ~100 mb over several hundred MeV, averaging 350 mb from 100 to 400 MeV.^{16,17} The p, p'; p, n; p, 2n; p, n reactions contain the majority of this cross section. For these reactions to trigger soft error, the recoiling target nucleus must be the agent for ionization energy deposition. Unfortunately, the recoil kinetic energy distribution has not been information of acute interest to nuclear researchers and often is lumped into the residual excitation energy. Thus, the fraction of the inelastic reactions which lead to a recoiling nucleus of sufficient energy to create soft error is not readily available.

Low-energy α particles already have been identified as a cause of soft errors in RAM cells. Thus one is bound to investigate reactions which produce α or larger fragments. The Si (p, α) reactions, as with all light nuclei, have relatively flat cross sections for $E_p \geq 100$ MeV at about 12 mb after peaking at 60 mb at 25 MeV.^{17,18} The Q value for He³ production is 16.9 MeV and for He⁴ is 7.7 MeV. At proton energies several times these, the p, α is a direct reaction, e.g., little residual nucleus excitation or recoil and, as a result, the α particles are produced in the forward direction at high energies ($E_p - Q$). In this energy range particles will have LET rates of the order of 5 keV/ μ and, in the dimensions of LSI (20 μ), cannot deposit the required energy (~5 MeV). It would require moderation (i.e., through shielding) of the incident proton flux to energies in the tens of MeV range to produce an abundance of α particles with low energies and high LET rates.

Spallation reactions have been measured¹⁹ in Al²⁷ and reflect total cross sections of about 6 mb for fragment production (i.e., F²⁰, O¹⁹, Be⁷). Although the fragments may differ with a Si²⁸ target, the strength of the cross section will not change much from Al²⁷. Thus, the combined p, α and p spall cross section (~17 mb for $E_p > 100$ MeV) leads to the following estimated reaction rates:

$$n \text{ reactions/year} = \phi_{\text{proton/yr}} \cdot \text{cm}^2 \cdot \rho N_A V \quad (9)$$

In the LSI case analyzed by Pickel and Blandford⁸ $V = 1030 \mu^3$ and $n = 2.3 \times 10^{-4} / (\text{year} \cdot \text{device}) = 23 / (\text{year} \cdot 10^5 \text{ device})$ due to p, α and p spall.

In a solar flare, proton flux levels increase dramatically by factors of as high as 10^5 for periods of the order of 24 hr. In such a flare (10^5 , 24-hr duration) the total number of p, α and p spall reactions in a 10^5 RAM would be ~6300. By using the total average inelastic cross section (350 mb), one would see 460 inelastic scatters per year per 10^5 devices for the cosmic-ray flux and 140,000 reactions in a solar flare of $10^5 \times$ cosmic flux lasting for 24 hr. The number of these which lead to soft errors is not easily known and requires the energy spectrum of the reaction products for solution. Although the event rate is small for each VLSI element (since the volume is $\sim 10^{-3}$ that of LSI), this is generally compensated for by the increased number of VLSI elements per chip.

Elastic Scattering

Consider a proton of kinetic energy 100 MeV incident on a Si nucleus, mass number 28. Assume that a transfer of greater than 100 keV is necessary by elastic collision for soft error to occur. The cross section is obtained from the integrated Mott-Rutherford relation for energy transfer greater than E_D .

$$\sigma_e = (\pi b^2 / 4\gamma^2) \{ (\epsilon - 1) - \beta^2 \ln \epsilon + \pi \alpha \beta [2(\epsilon^{1/2} - 1) - \ln \epsilon] \} \quad (10)$$

where

$$\gamma = (1 - \beta^2)^{-1/2} \quad \beta = v/c$$

$$\epsilon = E_m/E_D \quad \alpha = Z_2 e^2 / \hbar c$$

$$E_m = \frac{2E(E + 2mc^2)}{(1 + m/M)^2 mc^2 + 2E}$$

$$b = 2Z_2 e^2 / Mc^2 \beta^2$$

The m , v , β , γ , and E are proton parameters, Z_2 and M are for Si²⁸, and E_m is the maximum energy transfer possible. For an energy transfer, E_D , of 100 keV or greater resulting from 100-MeV proton elastic scatter, σ_e equals 208 mb. This is a value much larger than the p, α and p spall cross sections and implies that, for soft error thresholds of 100 keV, elastic scattering will contribute to soft errors. It should be noted that no devices currently available can be triggered by so little energy, but 100 keV is within the range of projection for VLSI.

Summary

1) The interaction of the heavy cosmic rays with satellite-borne microelectronics can be viewed along two lines: Soft errors (transient) and permanent damage. Soft errors can be avoided or reduced in number by several techniques; a) design in accordance with Eq. (7), b) fault tolerant circuitry, c) redundant programming. No consensus on the event rate at which soft errors become a "problem" exists at this time. Permanent damage in general cannot be shielded against but should not become a serious problem until device sizes reach VLSI. Failure levels can only be approximated until an experimental data base can be obtained from actual circuits.

2) Generation of soft errors from cosmic proton primaries by ionization loss along single tracks is not seen as a possibility for LSI/VLSI.

3) Proton generation of soft errors via elastic scattering reactions in Si^{28} become increasingly evident when protons of energy of a few tens of MeV are present and especially when the threshold energy for soft error reaches ~100KeV. Special notice should be taken of the vulnerability during solar flare time.

4) The number of nuclear reactions which will occur in volumes as minute as those characteristic of VLSI is very small. This is compensated by the increased number of elements per chip in VLSI. Thus, upsets caused by p, α ; p spall etc., reactions can still be anticipated. If the population of recoiling residual nuclei which result from inelastic scatter and which have energies greater than a few hundred keV is large, then nuclear inelastic scatter can contribute an event rate of concern. (During the publishing time of this article experimental verification of the proton initiated upsets has occurred.²⁰ The evidence suggests that inelastic scatter can produce events at LSI dimensions as well as at VLSI.)

5) The electronics package vulnerability assessment will require an analysis based on proton inelastic scatter products coupled with determination of the appropriate track distributions. Experimental and theoretical studies of these processes were undertaken in the past^{21,22} when semiconductors were much larger. The process needs to be repeated using current and projected LSI/VLSI circuitry to assess susceptibility to solar flare or trapped belt fluxes.

Conclusion

The response of VLSI circuitry to the particle fluxes encountered in Earth satellites can be partially anticipated from experience in nuclear survivability. Specifically, the knowledge of device behavior when exposed to fluxes of weakly ionizing particles which cause charge trapping in the oxides of MOS devices applies here. Soft error rates can be anticipated based on present experience with LSI memories in satellites or exposed to accelerator fluxes in the laboratory and on analyses of the kind presented here. The possibility of surprises exists because of permanent damage by heavy ion cosmic rays and the dramatically nonuniform dose distribution surrounding those ion tracks. Additional experimental work also is needed in the area of proton-nuclear reactions as they pertain to the creation of highly ionizing reaction products in electronics materials.

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